Man in a Cold Environment

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PHYSIOLOGICAL AND PATHOLOGICAL EFFECTS OF EXPOSURE TO LOW TEMPERATURES

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INTRODUCTION

The need for yet another book on the effects of low temperatures may reasonably be questioned, so a brief account of how this book came to be written appears to be desirable. In 1948, the Defence Research Board of Canada organized a conference at Toronto on the effects of cold on man, and in the discussion at that meeting, attended by research workers from the United States, Canada and Great Britain, there was widespread agreement that much of the wartime work, buried as it was in special military reports, would be lost, if someone who had been connected with the work did not publish it in a more available form.

Subsequently the Arctic Panel of the Defence Research Board raised the question again, and finally the authors contracted to prepare a book reviewing the wartime work, and bringing the subject as far as possible up to date.

The recent publication of two books on the same general subject, *The Physiology of Heat Regulation* edited by Newburgh, and *Temperature and Human Life* by Winslow and Herrington has made the task of writing this book much easier. Detailed description and explanation of technical points is adequately given in the first of these. Our hope is that there may be a place, in addition, for a more unified presentation of a consistent scheme of evaluating the problems of man in the cold than is possible to a large group of contributors. Also some aspects of the problem, particularly those of tolerance when heat balance is not possible, of the state of hypothermia, general and local, of the pathology of cold injury, and resuscitation from cold have hardly been discussed in any book. The new subject of 'acclimatization to cold' has been included because it is of such present interest, though as yet we have little data for man.

The book falls naturally into several divisions. In the first the physical and physiological problems involved in maintenance of a thermal steady state are discussed, with a scheme for assessing the thermal demand of the environment. In the second section the ways in which animals have met the problem are described, first in general terms, then in some detail as to physiological mechanisms in man. A section follows describing the consequences that result if heat balance is not maintained, leading eventually to pathology. Finally a chapter has been written suggesting the lines of future research that are indicated by our evident areas of ignorance.

We have tried to emphasize general principles rather than to give any detailed treatment of special cases. particularly in the discussion on clothing. There is already an extensive literature on this subject, mainly in the form of reports to Governmental committees, but there would be little point in citing them in a book of this kind. Again there are several ways of expressing the principles of heat exchange and of calculating the thermal demand of the environment. Our method is not necessarily the best, but we have emphasized it, in the conviction that it is worth sacrificing some broadness of view to secure consistency and simplicity of presentation.

In the course of preparation of the book it became obvious that some of the original aims would have to be modified. A very considerable number of wartime reports have been read, but the majority are not cited, as the physiological content of importance was generally found to be small. Fortunately, with a revival of interest in the subject, many of the wartime workers have returned to the field, so ensuring valuable continuity.

The literature on the various effects of cold is so extensive, it has been found impossible to cite every author. An attempt has been made to mention all the more important recent papers, but as all those who have ever had to prepare a review will know, as soon as the available literature has been read and a critical summary prepared, new publications will have appeared which modify previous work. We have therefore decided to make December 1951 the deadline. Some material published after that date has been included, but in most cases such material was available to us earlier in the form of a service report or by personal contact with the workers concerned. There has been no attempt to construct a complete bibliography as this has recently been prepared by the Office of Naval Research, and this bibliography has been of the greatest assistance to us. The late Dr. Geoghegan, working on behalf of the Royal Naval Personnel Research Committee had also been preparing a bibliography, and very kindly gave us permission to use his material. We have included in the text, data and discussion which have not been previously published. This was felt to be justified, as fragmentary information obtained in the course of *ad hoc* wartime research might be of some value, even though it would not obtain publication in the usual way.

However, the most important way by which we have obtained information of the current research on cold has been by direct personal contact with workers themselves. We have had the remarkable privilege of being able to discuss and watch work in progress in laboratories throughout Canada, the United States and Great Britain. Personal discussion has also taken place with those working in Scandinavia, Germany, Yugoslavia, etc. This has been due to the arrangement made on our behalf by the Defence Research Board of Canada, and the co-operation of the heads of service laboratories in the United States and Great Britain.

The help we have received is therefore very considerable, and we would like to take this opportunity to thank our colleagues, who have been so generous with information and advice. Inevitably we feel we have not been able to do justice to the material at our disposal, and we hope that our colleagues will realize that this book is not really meant for those already working in the field. Many papers which should have been cited have been omitted and we are only too well aware of the deficiencies. 'We offer you the repast: Now choose for yourself what you will eat.' (Dante, *Del Paradiso*, Book 10, line 25.)

Throughout the book temperatures have been expressed in degrees Centigrade with the Fahrenheit equivalent in brackets, except for calculations that are illustrative only. It is probably too much to hope that all workers will employ the Centigrade scale exclusively. After the meeting of the International Physiological Congress at Copenhagen, an informal gathering of some forty physiologists interested in climatic physiology was held. It was there agreed that the best policy at present would be to express temperature in degrees Centigrade with Fahrenheit in brackets. We strongly recommend this procedure to our colleagues.

We owe a special debt to Dr. Morley Whillans, head of the Defence Research Medical Laboratories, Toronto; he has encouraged us to continue with this book, and it is in large part owing to his stimulus that the book now appears.

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CHAPTER 1

HOMEOTHERMY AND HISTORY

Life and Thermodynamics

To some, it is still a matter of debate whether the existence and the growth of living cells and organisms is a contradiction, though perhaps a merely local contradiction, of the generalized second law of thermodynamics. This law, which has been given in so many ways that the lay person is apt to be confused, states that the entropy of the universe is increasing to a maximum, and this implies that the universe is becoming more and more uniform and randomized. The energy of the universe is always tending towards 'degradation' into the ultimate random motion we call heat. While the law, which is statistical in nature, permits us to suppose that in small regions of the universe, small enough to be below the applicability of statistics, local decreases of entropy in areas of high organization and differentiation can arise by 'statistical fluctuation', it seems incredible that the differentiation and organization of even a single living cell could be explained on the basis of such statistical fluctuations, even when recourse is had to the principle of selection in evolution and the facts of genetic inheritance (though Schrödinger (1) seems to think this enough). Living cells and organisms are so fantastically improbable that there does not seem to have been time enough for them to arise by fortuitous 'experiment' under the second law of thermodynamics. Life is considered as 'disentropic' by many, such as Ubbelohde (2).

Yet while the existence and proliferation of life is, on this view, in defiance of the second law, which seems to apply to all of the inanimate world which we are able to observe, the mode of life of cells and organisms, once they exist, is definitely in accordance with that law.

A good analogy is the automobile, which, being the product of the mind and activity of living organisms, is also a wildly improbable assembly of highly selected and organized molecules, and another contradiction of the second law. Yet the operation of the automobile, the way in which it runs uphill as well as down, is strictly in accordance with the law of entropy. The chemical energy of the fuel (petrol) is being degraded, a portion being transformed into mechanical energy but a great deal (over 70 per cent) appearing as heat at once. Even the mechanical energy eventually is degraded into heat in the friction of the moving parts and against the air through which the car has moved. When the car is back in the garage after the afternoon's drive, the end result is that all of the low entropy energy of the petrol used has been transformed into heat, and the entropy of the universe is correspondingly the greater.

So it is with living animals. Their life depends upon the production of heat from the chemical energy of food. By their existence they increase the 'flux of degradation' of energy in their locality. Possibly this flux is greater than it would be if the world were all inanimate, and living things somehow 'pay for' their special privileges of emancipation from the second law, by their increased contribution to the general trend.

As to the application of the first law of thermodynamics, the conservation of energy principle, the long series of researches of Lavoisier, Richet, Zunst, Lusk and a host of others culminated in the work of Benedict and Atwater, DuBois and Murlin, to show that, without a shadow of a doubt, all of the energy that appears ultimately as heat is quantitatively accounted for by the chemical energy of the food ingested. We will be concerned with both of these laws of thermodynamics, in part with the first law in the chapters on nutrition in the cold and in consideration of the heat production of man, and a great deal with the second law, in consideration of the transfer of the degraded energy, the heat-loss, to the universe about us.

The 'Excess Temperature' of Living Cells

One consequence of the second law of thermodynamics (and this is the one emphasized in textbooks of thermodynamics since originally the law was developed from considerations of heat engines, long before the broad applications were appreciated) is that heat flows only from regions of higher temperature to where the temperature is lower. Thus the 'energy flux' of a living animal cannot reach a steady state of exchange with its environment until the temperature of the animal has risen above that of its surroundings. The temperature reached by the cells of the animal will be determined by the turnover of energy of the cells and also by the ease with which the heat so produced can diffuse to the surroundings, for the law of diffusion of heat states more than that it must flow from higher to lower temperatures (which is all the second law demands). The 'thermal gradient' down which the flow occurs is quantitatively related to the flow. The greater the heat produced by the energy turnover, the greater the excess of the temperature of the animal over that of its surroundings. We might depict the situation graphically as in Fig. 1*A*, where we have for simplicity assumed that the flow of heat is proportional to the excess temperature (this is approximately true). Thus the temperature of the tissues of an animal is determined by the activity or energy consumption of those tissues and by the way in which heat can flow down the thermal gradient, i.e. by the 'thermal insulation'. This is treated in more detail, and quantitatively, in succeeding chapters.

The Universal Effect of Temperature on Life

If the factors illustrated by Fig. 1*A* were all that must be considered, the study of the energy exchanges of animals and man would be fairly simple, though possibly rather dull. However, we cannot consider the rate of energy turnover as something determined by the animal, by its organization, enzymes and so on, and by that alone. The temperature of cells also directly affects their activity. The life of the organism depends upon the chemical reactions by which the entropic transformation of chemical energy into heat is proceeding. The rate of these chemical reactions, universally, is affected by their temperature.

The dependence of the rate of reactions upon the temperature is well expressed, for the great number of cases, animate and inanimate, that have been studied, by the well-known law of Arrhenius. This law states that the logarithm of the rate is proportional to the reciprocal of the Absolute Temperature. The law has no solid foundation of proof by thermodynamics, though kinetic theory has almost succeeded in giving it scientific respectability. The increase in velocity constant of a reaction, by this law, is not linear but rather logarithmic with temperature, so that as the temperature rises, the increase is accelerated. The temperature coefficient is often described by the Q_{10}, which gives the ratio of increase of rate with a rise of 10°C in temperature. For most metabolic processes the Q_{10} is between 2·0 and 3·0, i.e. the heat production of living cells will increase two to three times if their temperature is raised by 10°C. We may therefore depict the second relation between the energy flow of organisms and their temperature by a second graph, Fig. 1*B*. In this case we must use a curve rather than a straight line.

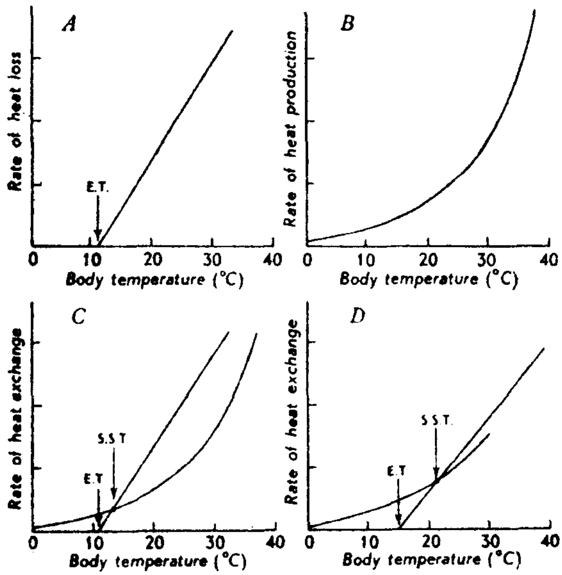

FIG. 1. Thermal exchanges in the poikilotherm. (*A*) Relation between heat loss and temperature of tissues. E.T. Environmental Temperature, taken in this case as 11°C. (*B*) Relation between heat production and temperature of tissues according to the Arrhenius relation. (*C*) Combination of *A* and *B*. S.S.T. Steady State Temperature, given by the intersection of the lines. (*D*) Increase of Steady State Temperature (S.S.T.) when the Environmental Temperature (E.T.) is increased from 11°C to 15°C.

Both of these relations must hold simultaneously, i.e., the temperature of the tissues is determined by the physical relation between excess temperature and heat loss, and also by the chemico-physical relation between temperature and heat production. Thus for the steady state we must combine the two graphs (Fig. 1*C*). The only possible steady state of the cells in these circumstances of environmental temperature is represented by the intersection of the two lines on the combined graph. The operation of these two laws, that of diffusion of heat and that of Arrhenius, impose a restriction on the freedom of the operation of the living animal. An animal cannot, according to these considerations alone, increase its activity without a change in the temperature of the tissues. Again, the temperature of its tissues, and therefore the biological activity of the animal, will depend upon the environmental temperature, since there is a new 'heat loss line' for each environmental temperature and a new point of intersection of the two lines (Fig. 1 *D*).

Thermodynamics has therefore imposed upon the living organism a severe restriction of its freedom of action. The study of this restriction and how it has been modified by special mechanisms in some animals (the homeotherms) is the subject of this book. Other studies, such as the consequences of the restriction that are involved when a cell or whole organism grows, or the stability of the state represented by the intersection on the graphs (3, 4), are beyond the scope of this book.

The 'poikilotherm', not possessing the means to escape from these 'fetters of thermodynamics', is almost the slave of the environmental temperature. All that one has to do to reduce the dangerous alligator to a helpless state for physiological experimentation is to leave him in the ice-box for a few hours. We are told that the world was at one time populated by poikilothermic animals of fantastic size and strength, and presumably speed. Yet their life must have been at the mercy of the climate. On a cold day the battle of existence slowed to relative inactivity. Before the development of the special group of animals called homeotherms, possessing the power, within limits, to be emancipated from thermal slavery, the temperature must have played a much less important rôle in the story of evolution. The outcome would be little affected when both pursuer and pursued were slowed by a fall of temperature. But the puniest homeotherm, like the little shrew, could survive against its poikilothermic enemies, when it was able still to be active in the cold. Perhaps the dependence of the large poikilotherms upon the temperature was the chief factor in the extinction of most of their species, once they had to compete with others less powerful but enjoying thermodynamic freedom.

The Advantages of a Constant Brain Temperature

We have considered the advantages possessed by the homeotherm in terms of independence, within limits, of the tissue temperature from the environmental temperature. Such independence would not necessarily imply constancy of the deep body temperature. In the homeotherms we find that the deep body temperature, which is approximately the same for the 'core' of the body (e.g., deep rectum, viscera, liver, brain) is regulated to constancy within a remarkably narrow range of temperature; in the human about 36·4 to 37·5°C (97·5 to 99·5°F) with a diurnal rhythm.

It is of interest to inquire why such a constant temperature is desirable. A very reasonable hypothesis is that the greater the complexity of the integration of the organism, the greater is the need for constancy of temperature for efficient functioning. All chemical, and physical, reactions change their rate with change of temperature, but the degree of acceleration with rising temperature is different for different reactions. Extension of the theory of Arrhenius by the physical chemists predicts that the dependence of the velocity constant of a reaction upon temperature will depend upon the 'activation energy' (a measure of the energy required for the initiation of the reaction rather than the energy liberated when it proceeds). Activation energies in biological reactions vary widely. Thus when we have a complicated process involving the co-ordination of many individual reactions, a rise of temperature will not only speed the over-all rate but will alter the relative rates of the various reactions involved. If the brain were like a clock mechanism, we might imagine that a change of temperature would result in throwing the various reactions out of step with each other. The analogy is false, for the law of mass action applied to a complex of successive or interlocking reactions shows that there is a type of automatic stability by which the reaction rates are changed to keep 'in mesh' whenever one of them is altered. However, the relative concentration of all the reactants will be markedly different when the new steady state, at a different temperature, is reached, and thus side reactions, connected with these reactants, will change their relative importance. Change of temperature therefore produces not only a change of over-all rate of metabolic and other biological processes, it also changes the qualitative character of these processes. It is easy to see how the human brain, where we think the integrative co-ordination of many processes is most developed, will be greatly disturbed by change of its temperature, while simpler, more unitary processes, as in the brain of lower forms or the peripheral tissues of man, will be less affected. Experience confirms that only a slight change in brain temperature, as in fever (even in non-toxic, artificial fever) or hypothermia, does result in profound confusion in mental processes.

Confirmation of this idea that it is complexity of organization that makes homeothermy necessary to an animal is the interesting fact that very young animals, in which the full co-ordination and